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M. Frey, J. Snuverink, C. Baumgarten, A. Adelmann :: SNSF project 200021_159936 :: Paul Scherrer Institut

Application of multi-objective optimisation to match turn pattern measurements for cyclotrons

15/04/2019 :: GFA Seminar

Thesis advisor: Prof. Dr. Klaus S. Kirch
Thesis supervisor: Dr. Andreas Adelmann

Outline

- Motivation
- New Trimcoil Model in OPAL
- Multi-Objective Optimisation
- Local Search
- Final Results & Conclusions

Obtain Isochronicity in Cyclotrons

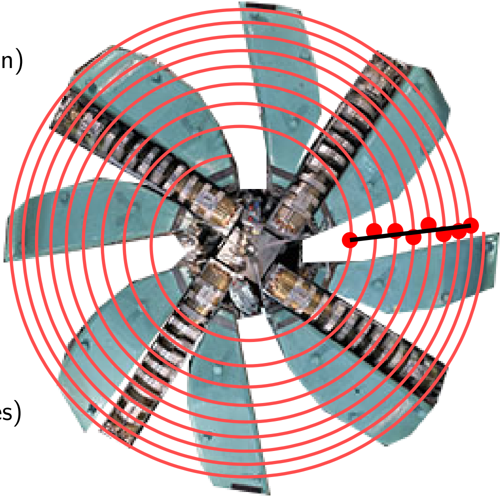
- **Discrepancies / Error** in
  - magnetic field (calculation and construction)
  - **injection** parameters ($E_{kin}, r, p_r, \ldots$)
  - element **positioning** (RF cavities)
  - etc.
- **Restored / Achieved:**

  Additional B-field with **trimcoils** (TCs)

  $\Longrightarrow$ phase shift

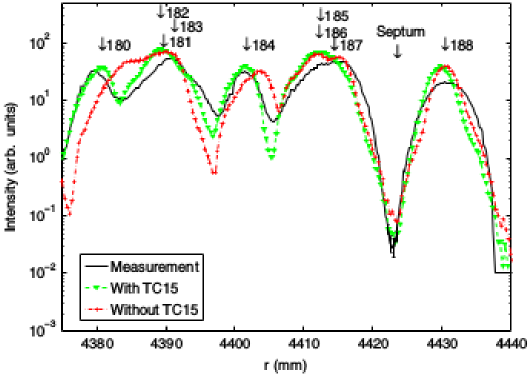
  (beam gets more/less energy by RF cavities)

  $\Longrightarrow$ turn radius shift



Mismatch between Measurements and Simulations

- **Discrepancies / Error** in
  - measured magnetic field due to **measuring conditions**, **technique** and **machine accessibility**
  - **simulation model:**
    - discretisation in time and space
    - simplified device models
    - missing device models
    - etc.
  - **injection** parameters ($E_{kin}, r, p_r, \ldots$)
  - element **positioning** (RF cavities)
  - etc.



Towards quantitative simulations of high power proton cyclotrons.

Y. J. Bi, A. Adelmann, R. Dölling, M. Humbel, W. Joho, M. Seidel, and T. J. Zhang. Phys. Rev. ST Accel. Beams 14, 054402

Towards More Realistic Trimcoil Simulations

- OPAL PSI-Ring model only TC15

  but 16 TCs (TC17/18 not used) in PSI-Ring Cyclotron

- TC-model in OPAL approximated using analytical model mimicking profile

  but there are TC measurements available

- TC-field contribution in OPAL for 360 degree

  but in reality only on sector magnets

New Trimcoil Model in OPAL

- Radially rational TC profile description

$$TC(r) = B_{\max} \frac{\sum_{i=0}^{n} a_i r^i}{\sum_{j=0}^{m} b_j r^j} \qquad n, m \in \mathbb{N}_0 \wedge r \in [r_{\min}, r_{\max}]$$

```
tc1:  TRIMCOIL, TYPE = "PSI-PHASE",
                RMIN = ..., // inner radius [mm]
                RMAX = ..., // outer radius [mm]
                BMAX = ..., // B-field peak value [T]
                COEFNUM   = {a0, a1, a2, a3},
                COEFDENOM = {b0, b1, b2, b3, b4, b5};
```

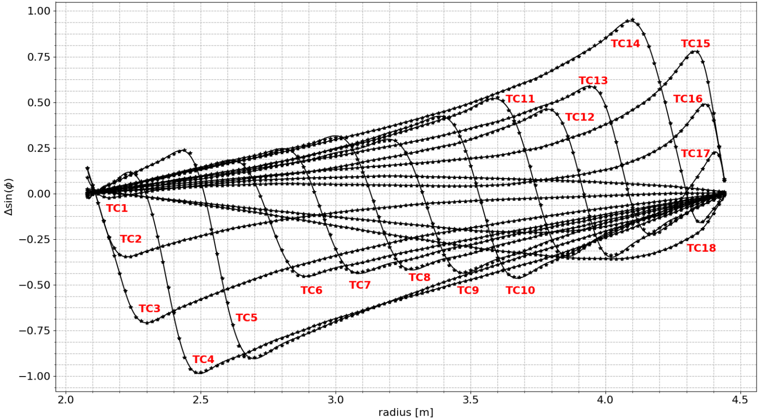
New Trimcoil Model in OPAL

- **Supported types:**
  - new: PSI-BFIELD, PSI-PHASE
  - old: PSI-BFIELD-MIRRORED
- **Cyclotron-Definition:**

```
Ring: CYCLOTRON, TRIMCOILTHRESHOLD = ...,
                 // lower limit of TC contribution [T]
                 TRIMCOIL = {tc1, tc2, tc3, ...}
                 ...
                 ;
```

PSI-Ring Trimcoil Model

- **Starting point:** Measurement of phase shift effect[1] $\Delta B \sim -\frac{d\Delta \sin(\phi)}{dr}$



[1] S. Adam and W. Joho, PSI Technical Report No. TM-11-13, 1974.

PSI-Ring Trimcoil Model

- **Fit of phase shift curves:**

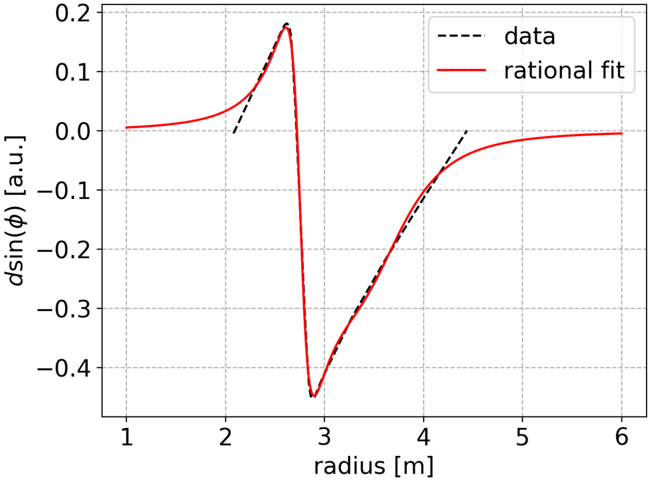
$$\Delta \sin(\phi)(r) \approx h_{phase}(r) = \frac{f(r)}{g(r)} = \frac{\sum_{i=0}^{n} a_i r^i}{\sum_{j=0}^{m} b_j r^j}$$

  with $m > n \in \mathbb{N}_0$

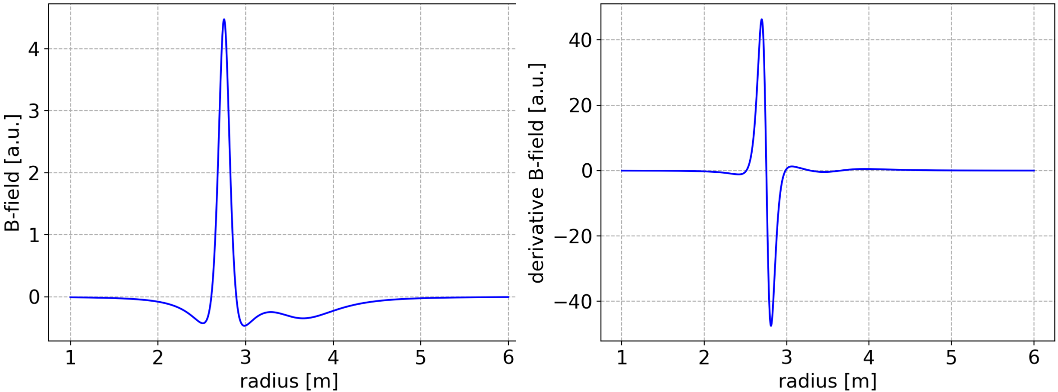
- **TC2 - TC15:** $n = 2, \; m = 4$
- **TC1, TC16 - TC18:** $n = 4, \; m = 5$
- **Magnetic field:**

$$B(r) = -\frac{dh_{phase}}{dr} = -h'_{phase} = -\frac{f'g - fg'}{g^2}$$

PSI-Ring Trimcoil Model - Example TC6



PSI-Ring Trimcoil Model - Example TC6



Multi-Objective Optimisation (MOO) in OPAL

- **Built-in MOO**[2]:

$$
\begin{aligned}
&\min && \mathbf{f}(\mathbf{x}), && \dim(\mathbf{f}) \geq 1 \\
&\text{s.t.} && \mathbf{g}(\mathbf{x}) \geq 0, && \dim(\mathbf{g}) \geq 0 \\
& && -\infty \leq x_i^L \leq \mathbf{x} = x_i \leq x_i^U \leq \infty, && \mathbf{x} \in \mathcal{X} \subset \mathbb{R}^n, \quad n \in \mathbb{N}^{>0}
\end{aligned}
$$

- **Design variables x:** E_{kin}, p_r, φ, TC1 - TC16 max. B-field, etc.
- **Objectives:** Measure between simulation and real data

Note: f is our PSI-Ring model + evaluation of objectives!

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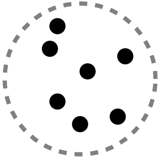
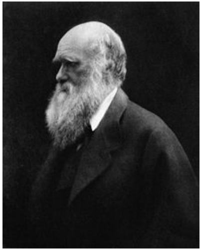
[2] Toward massively parallel multi-objective optimisation with application to particle accelerators. PhD Thesis. Y. Ineichen. 2013

Multi-Objective Genetic Algorithm (MOGA)

1^{st} generation

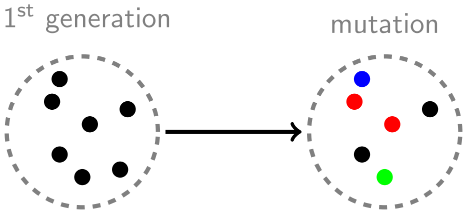


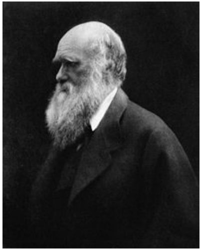


Charles Darwin[3]

[3] Image:https://en.wikipedia.org/wiki/Charles_Darwin

Multi-Objective Genetic Algorithm (MOGA)





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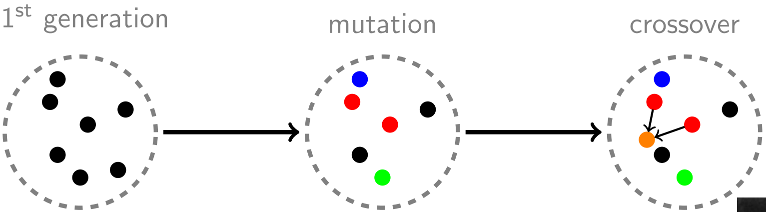

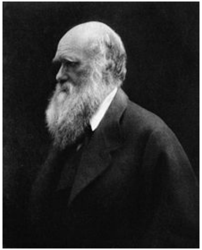

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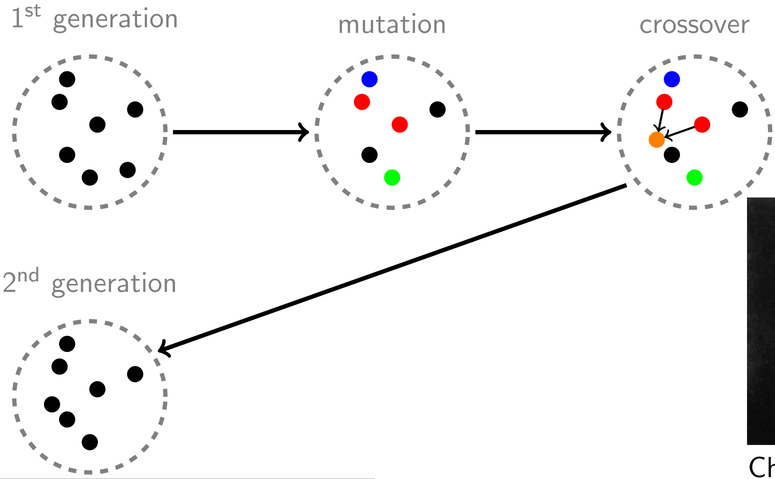

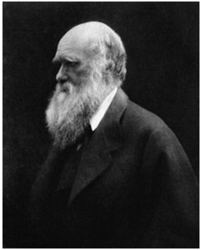

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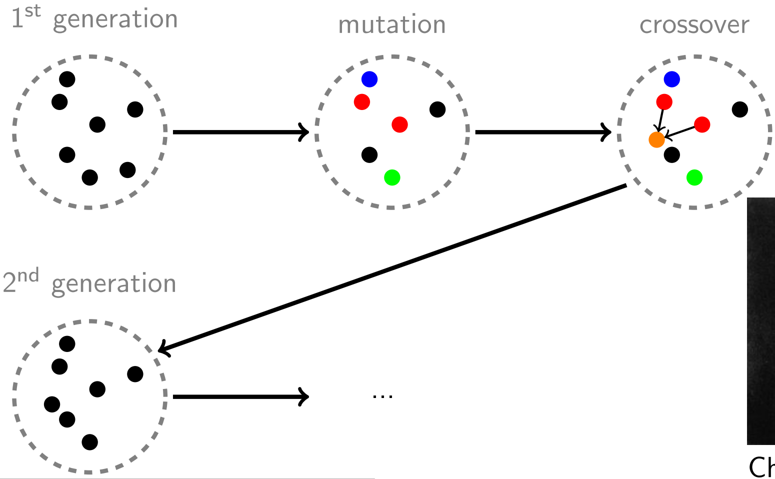
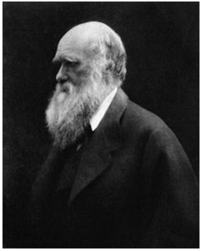




Charles Darwin[3]

[3] Image:https://en.wikipedia.org/wiki/Charles_Darwin

Radial Profile Measurement – Centred Beam

- **Measurements:** Peak intensity of radial profile of probes to distinguish turns

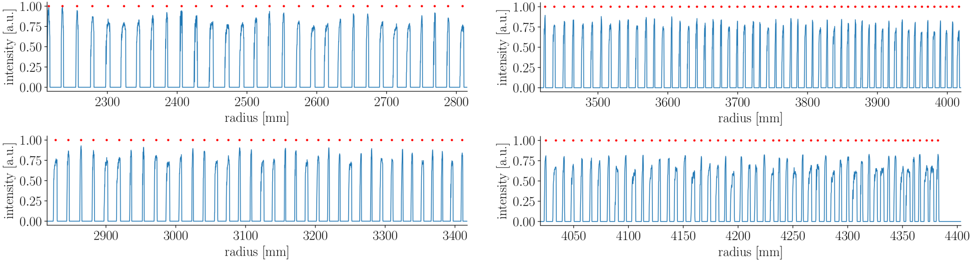
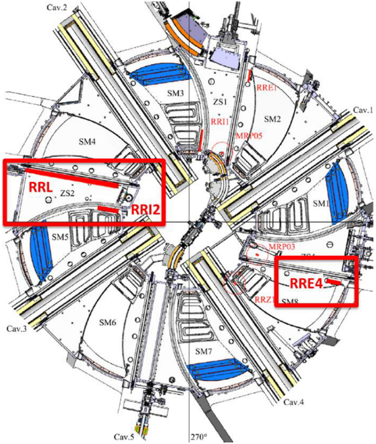


Figure: Histogram of RRL measurement

Trimcoil Optimisation in OPAL

- **Simulations:**
  - **Single particle** ⇒ probe hit = turn
  - **Multi particles** ⇒ peak finder routine
- **Good setting:** Radial peak of measurement and simulation at probes are close!
- **RRI2:** turns 1 - 16
- **RRL:** turns 9 - 182



OPAL simulations of the PSI ring cyclotron and a design for a higher order mode flat top cavity. N. J. Pogue, A. Adelmann. Proceedings of IPAC2017. THPAB077. 2017.

182 turns ⇒ Infeasible number of objectives!

Problem Reduction

- **Turn - Aggregation:**
  - L_2-norm

$$\sigma_{[l,u]} = \frac{1}{N}\sqrt{\sum_{i=l}^{u}(r_i^m - r_i^s)^2}$$

  - L_∞-norm

$$\sigma_{[l,u]} = \max_{i=l\ldots u} \left| r_i^m - r_i^s \right|$$

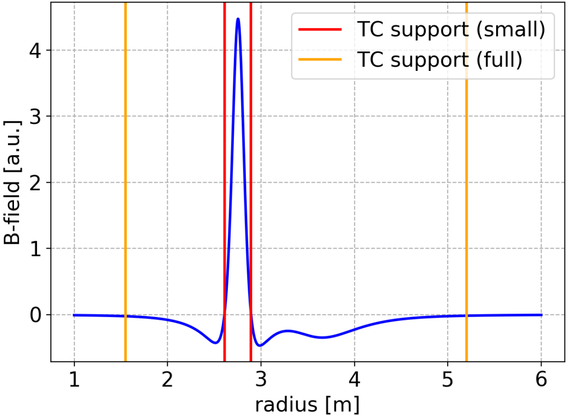
$N = u - l + 1$: number of aggregated turns

r_i^m: i-th turn radii of measurement

r_i^s: i-th turn radii of simulation

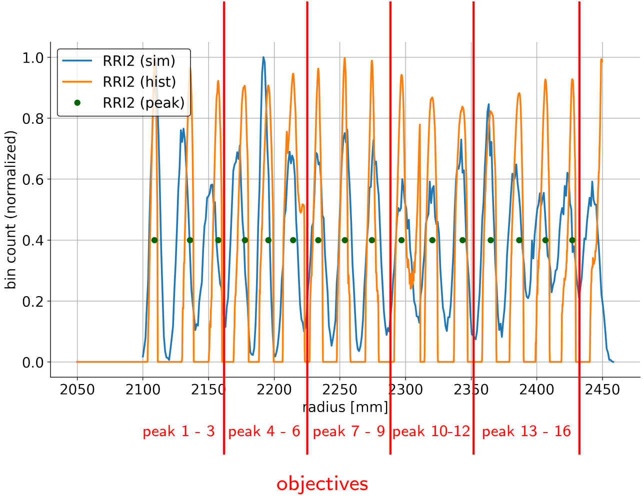
Problem Reduction

- **TC support reduction:**
  Feasible assumption for neighbouring TCs ⇒ Cancellation of B-field tails



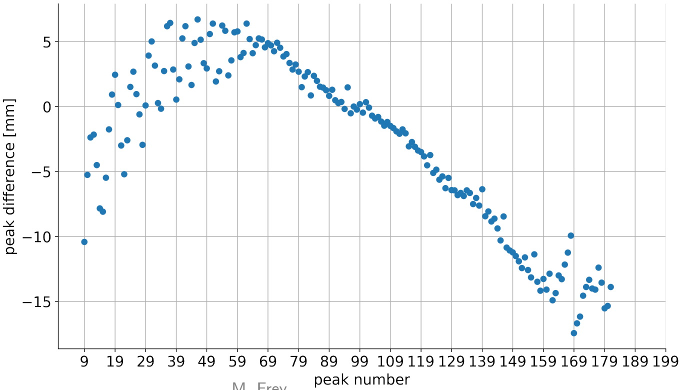
Trimcoil Optimisation in OPAL - Trial 1

- **Goal:**
  Find initial injection values
- **Design variables:**
  - beam energy E_{kin}
  - injection angle
  - injection momentum
  - injection radius
  - TC1 - TC4
- **MOO:** (504 cores)
  #generations 500 +
  #individuals 502
- 5000 particles per individual



Issue of Divergence - Trial 1

- Optimising a few TCs after the others (i.e. optimise sub-problems) lead to divergence!
- RF cavity voltages not correct → more design variables needed!



Model Simplification + Design Variable Extension

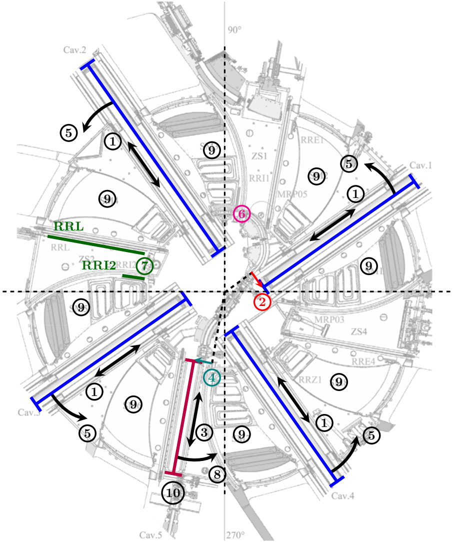
- **Single particle tracking** instead of bunch (5000 particles) tracking

  $\Longrightarrow$ full PSI-Ring simulation in 1 - 2 s

- **Design variables:**
  - injection angle, radius, momentum and energy
  - main cavity voltages
  - phase of Flat-Top cavity
  - voltage of Flat-Top cavity
  - radial position of main cavities
  - radial position of Flat-Top cavity

- **Turn number constraint** to guarantee feasible solutions

Design Variables in Context of Cyclotron



① main RF cavity displacement in radial direction; RF voltage on main cavity 1 - 4

② displacement of main cavity's axis from global center

③ flat top cavity displacement in radial direction

④ displacement of flat top's axis from global center

⑤ main cavity's angle w.r.t. the center line of sector magnet 1

⑥ injection beam energy, injection radial momentum, injection angle of beam, injection radius w.r.t. the global coordinate system

⑦ positioning of probes (6 parameters)

⑧ flat top cavity angle w.r.t. global coordinate system

⑨ trim coil maximum magnetic field

⑩ phase of flat top; RF voltage on flat top cavity

Evolution of best individual during MOGA

>8k individuals/generation

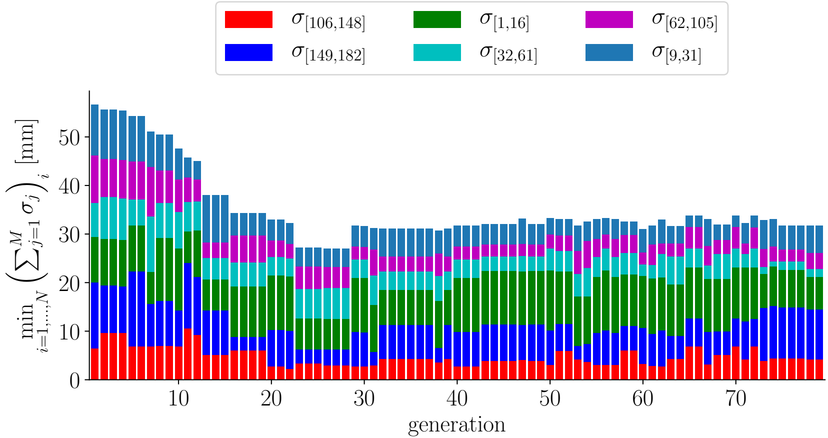


Figure: The label $\sigma_{[l,u]}$ indicates an objective for the turns in the range $[l, u]$. M: number of objectives; N: number of individuals per generation.

Result of best individual obtained by MOGA

Objective $\sigma_{[l,u]}$	l_∞-error (mm)	Probe
$\sigma_{[1,16]}$	6.38	RRI2
$\sigma_{[9,31]}$	3.76	RRL
$\sigma_{[32,61]}$	6.34	RRL
$\sigma_{[62,105]}$	4.39	RRL
$\sigma_{[106,148]}$	2.91	RRL
$\sigma_{[149,182]}$	3.27	RRL

Table: The label $\sigma_{[l,u]}$ indicates an objective for the turns in the range $[l, u]$.

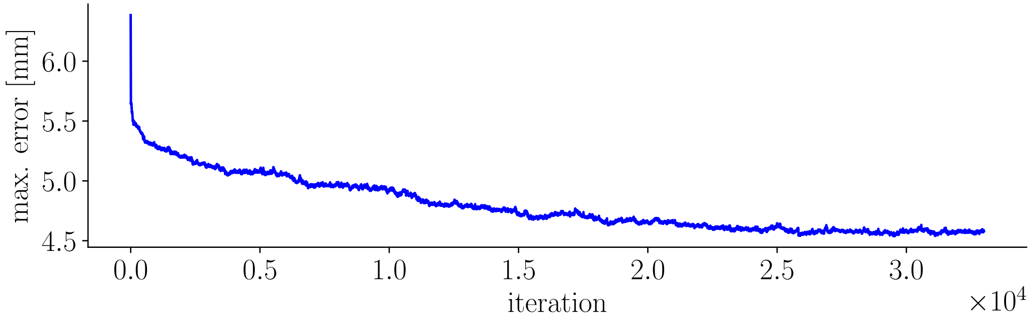
Local search after MOGA

- **Issues:**
  - Optimiser suffered with individual selection
  - No further improvements!
  - Changing all parameters at same time might be disadvantageous
- **Idea:** Do simple parameter scanning!
  - Python script (1 core)
  - Starting from best MOO individual
  - Iteratively find worst turn and vary parameters to obtain better individual

    (check L_∞- and L_2-norm, 2nd and 3rd worst turn to avoid getting stuck with only L_∞)
  - Change a input parameter only in per-mille magnitude

Evolution of maximum absolute error during local search

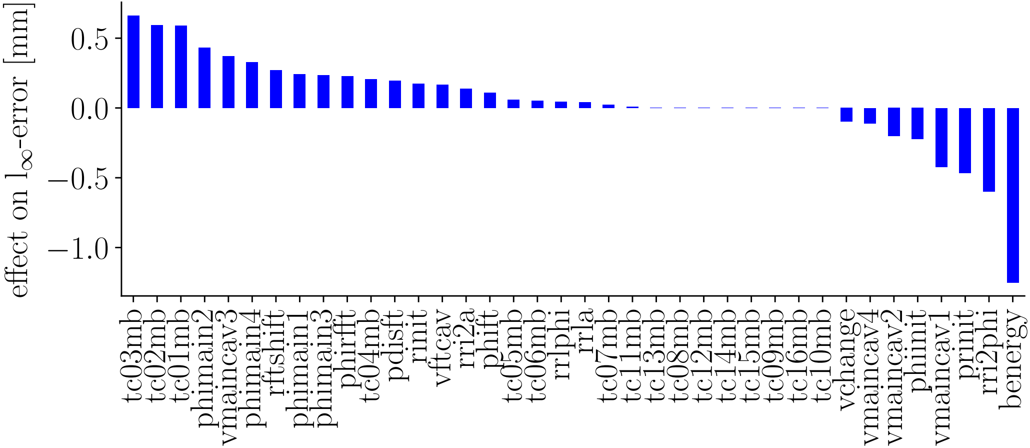
> 1 mm error reduction after a few iterations



Total effect on max. absolute error per design variable.

$>$ 0 error reduction

$<$ 0 error increase



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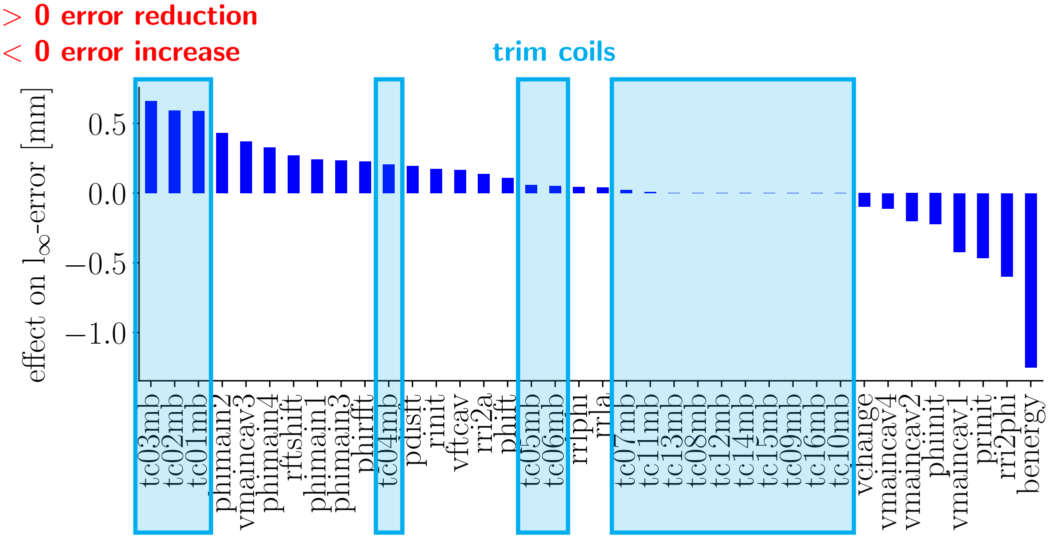
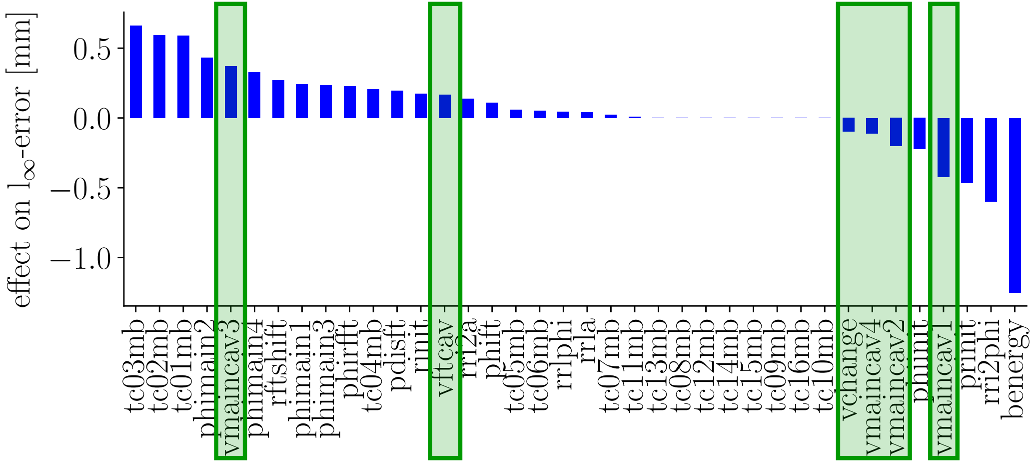


Total effect on max. absolute error per design variable.

> 0 error reduction

< 0 error increase

RF cavity voltages



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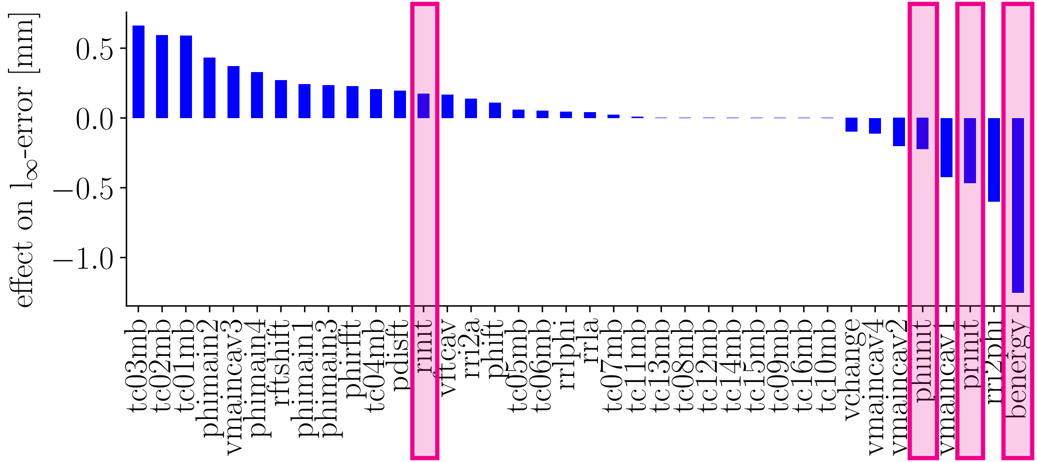
Total effect on max. absolute error per design variable.

> 0 error reduction

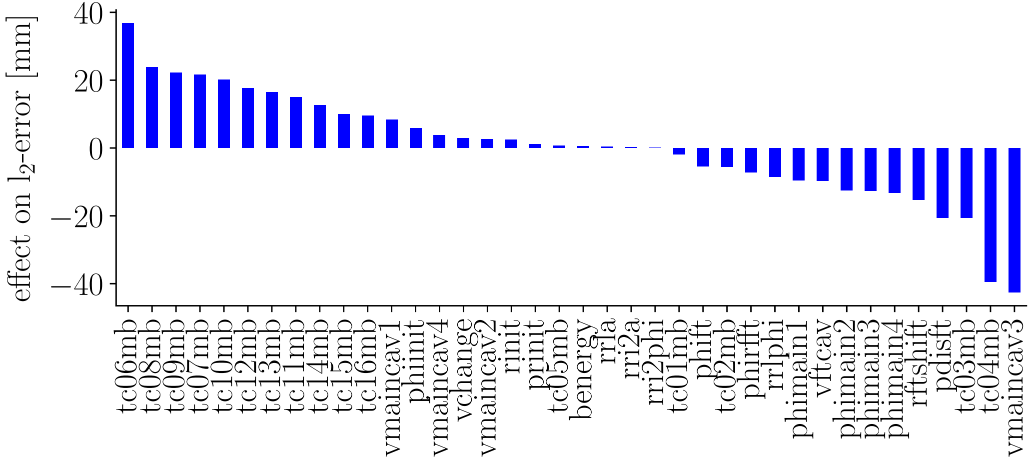
< 0 error increase



Total effect on l_2 error per design variable (DVAR)

$>$ 0 error reduction

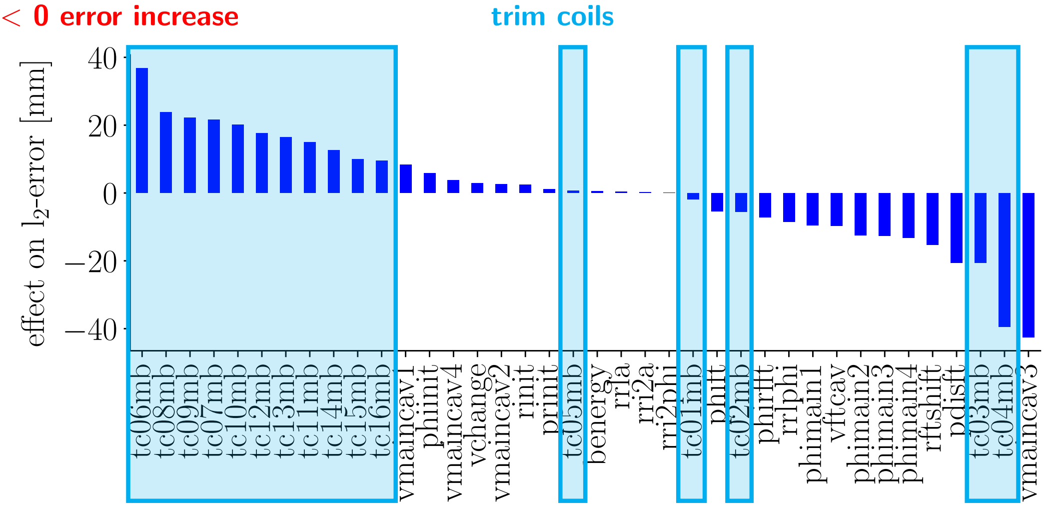
$<$ 0 error increase



Total effect on l_2 error per design variable (DVAR)

> 0 error reduction

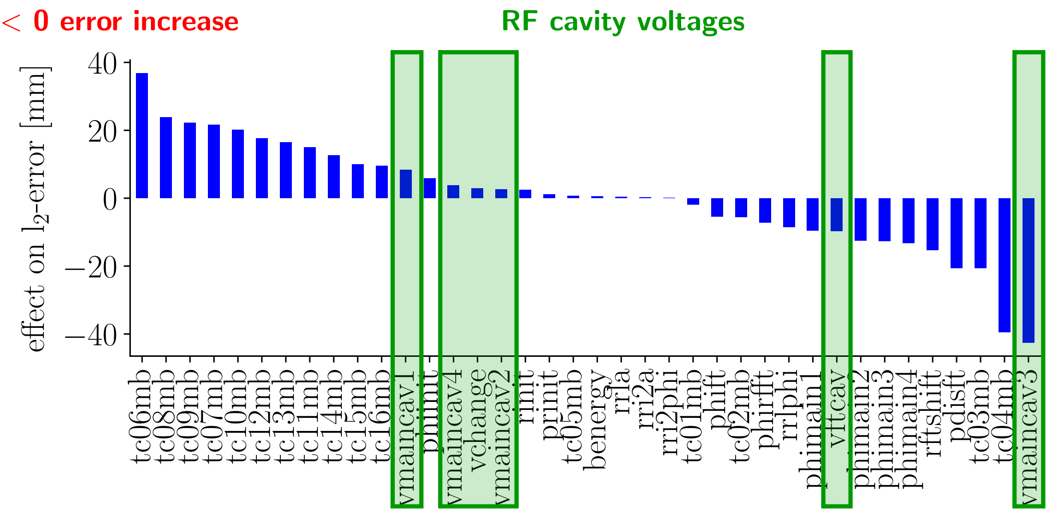
< 0 error increase



Total effect on l_2 error per design variable (DVAR)

>0 **error reduction**

<0 **error increase**

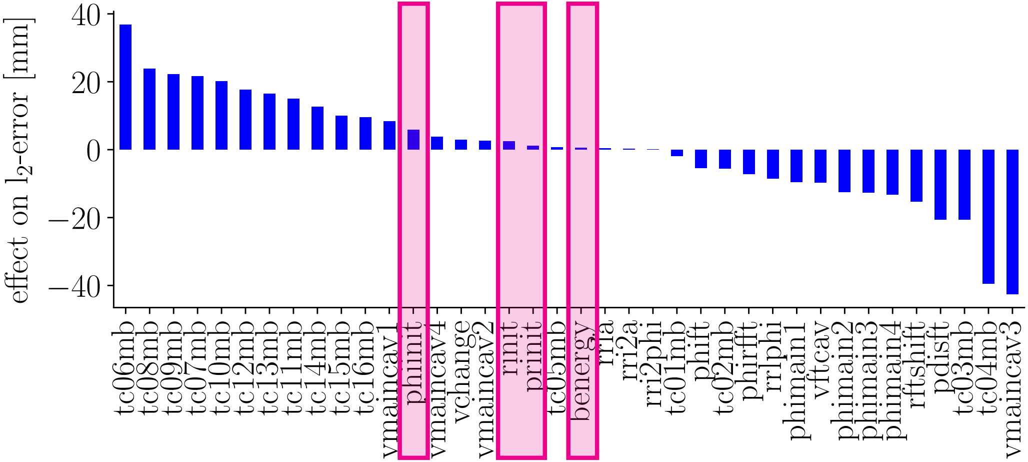


Total effect on l_2 error per design variable (DVAR)

$>$ 0 error reduction

$<$ 0 error increase

beam injection parameters

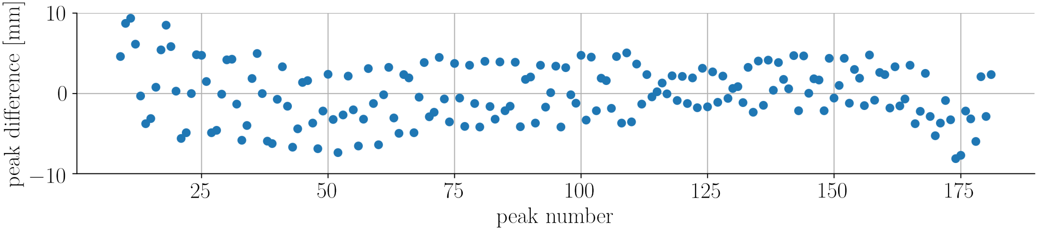


Summary on Effect

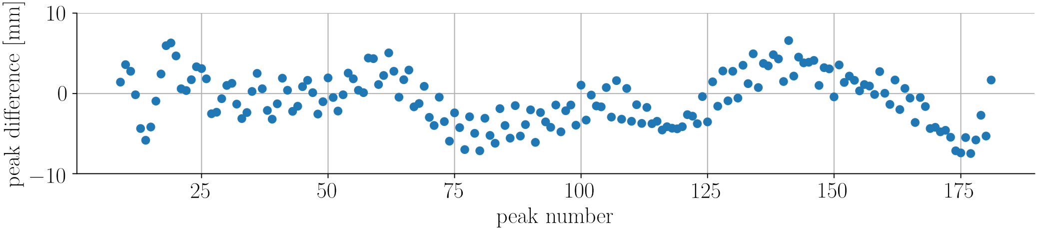
- **Maximum absolute error:**
  - TC1 - TC6 have a positive effect
  - TC8 - TC16 do not improve / harm
  - Except to initial radius, beam injection parameters negative effect
  - RF voltages mixed effect
- **l_2 error $\sim$ error smoothness:**
  - TC1 - TC4 have negative effect
  - TC5 almost no effect
  - TC6 - TC16 decrease non-smooth behaviour
  - Beam injection parameters almost no effect
  - Main cav 3 voltage strong negative effect

Wiggly Solution due to TCs - Long Probe RRL1

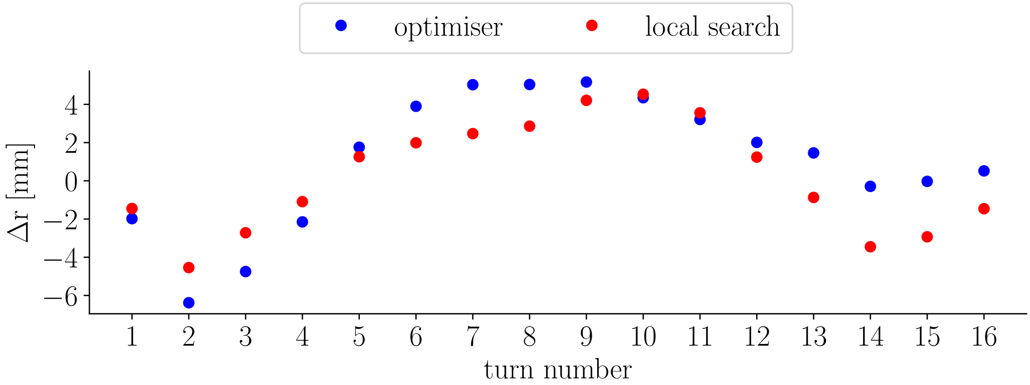
Optimisation (subset of DVARs) with TCs disabled



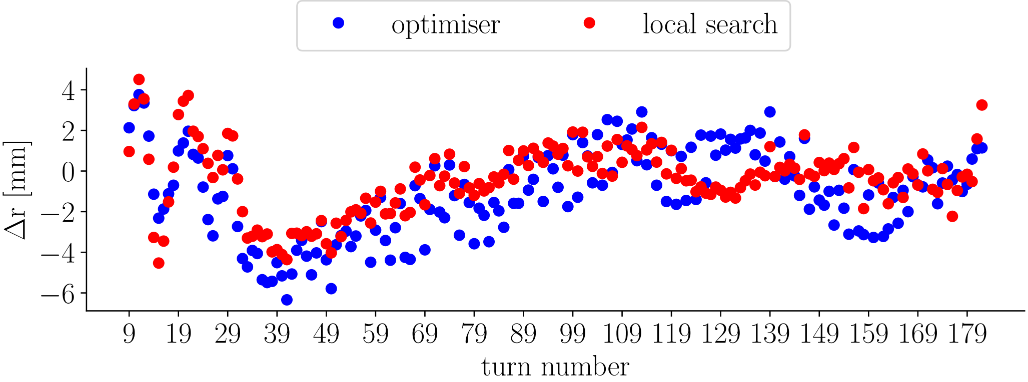
Optimisation of above with TCs only



Final Results - RRI2



Final Results - RRL



Final Results

Method	l_∞-norm (mm)	MAE (mm)	MSE (mm^2)
optimiser	6.4	2.0	6.3
local search	4.5	1.4	3.4

Table: Maximum absolute error (l_∞-norm), mean absolute error (MAE) and the mean squared error (MSE) of the best individual of the optimiser and local search compared to the measurement. In both cases the maximum error is at turn 2.

Conclusions

- New Trimcoil model
  - successfully implemented and tested
  - more realistic
- Multi-Objective Optimization (MOO) in OPAL
  - massively parallel (used with $> 1'000$ cores)
  - suffers with individual selection in case of high-dimensional design variable space
  - other algorithms should be considered (e.g. simulated annealing)
  - to improve a simulation model (matching with measurements)
- Local search of design variables
  - improved error of simulation vs. measurement
  - may get stuck and stop improving (combination of L_∞- and L_2-norms helps)
- Please check out arXiv:1903.08935 (submitted to Phys. Rev. AB)

Thanks to

H. Zhang

M. Humbel

R. Dölling

W. Joho

M. Kranjčevic

Backup - Multi Particle Tracking

Comparison to	l_∞-norm (mm)	MAE (mm)	MSE (mm^2)
measurement	4.64	1.46	3.59
space charge	0.05	0.00	0.00

Table: Maximum absolute error (l_∞-norm), mean absolute error (MAE) and the mean squared error (MSE) of the measurement or multi particle tracking simulation including space charge to the multi particle tracking simulation neglecting space charge.